Dark and Visible Photons as Source of CP Violation

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The problem of excess gamma radiation in the center of galaxy is discussed assuming that the photon's production is dominated by two kinds of processes, the first one due to the conventional kinetic mixing term and, secondly, due to a kinetic mixing term violating the CP symmetry between dark and visible photons. The CP violation symmetry between dark and visible sectors is not forbidden and, in principle, could be considered as an additional source of CP violation. The conversion probability between dark and visible photons is calculated and compared between both processes. The processes violating CP are less significant but contribute non-trivially to the excess gamma radiation.

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The detection of dark matter and their constituents are two entangled problems subject to an intense theoretical and experimental scrutiny [1]. Generally speaking, since we still do not know all the symmetries which fully describes visible and dark matter, our predictive ability is still limited [2].

On the other hand, there are several observational results which could find a natural explanation from the particle physics point of view if both kind of matters and their interactions find a place in an unified model. One of them is the excess of gamma radiation from galaxies center. Most likely, as is discussed in many papers [3, 4], such photons are produced by annihilation of pairs of dark matter (d) and anti-dark matter ($\bar{d}$) in high density region producing gamma radiation [5, 6].

However, although the hypothesis $d + \bar{d} \to$ photons is very reasonable, we cannot assure that in the dark sector there are processes that respecting all the obvious symmetries of standard particle physics. One of symmetries not necessarily fulfilled is CP symmetry (although CPT continue be an exact symmetry) and therefore, this is an issue that deserves to be studied.

Consider dark (X_μ) and visible photons (A_μ) whose interactions may appear as kinetic mixing and can be implemented in different ways, one of them and the best known, is by adding to the $U(1) \times U'(1)$ Lagrangian, the kinetic mixing term [7] (for recents developments see *e.g.* [8])

$$F_{\mu\nu}(A) F^{\mu\nu}(X) \equiv F(A) F(X). \tag{1}$$

In order to explain this idea let us assume a massive charged fermion (ψ), a visible photon (A_μ) and a dark one (X_μ) which interact by means of the following $U(1) \times U'(1)$ theory

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\partial\!\!\!/ - A\!\!\!/ - m)\psi - \frac{1}{4e^2} F^2(A) - \frac{1}{4} F^2(X) + \frac{\chi}{2e} F(A) F(X) \\ &= \mathcal{L}_f + \mathcal{L}(A, X),\end{aligned} \tag{2}$$

where e is the charge of the fermion and

$$\mathcal{L}(A, X) = -\frac{1}{4e^2} F^2(A) - \frac{1}{4} F^2(X) + \frac{\chi}{2e} F(A) F(X). \tag{3}$$

The last Lagrangian can be diagonalized through the transformation $X'_\mu = X_\mu - (\chi/e)\, A_\mu$ and, after this transformation it turns out to be

$$\mathcal{L} = -\frac{1}{4(e_{(-)})^2} F^(A) - \frac{1}{4} F^2(X'), \tag{4}$$

and therefore (2) becomes

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - e_{(-)} A\!\!\!/ - m)\psi - \frac{1}{4} F^2(A) - \frac{1}{4} F^2(X'), \tag{5}$$

where χ is a real parameter and then, the effect of kinetic mixing is to redefine the electric charge [9]

$$e_{(-)} = \frac{e}{\sqrt{1 - \chi^2}}. \tag{6}$$

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Naively the redefinition of the electric charge (6) could be seen as a simple renormalization, however for $\chi^2 > 1$, the kinetic energy for A changes sign, ghosts appear and unitarity is lost.

In consequence, this rescaling (6) is applicable only if $\chi^2 < 1$. If $\chi = 1$, $U(1) \times U'(1) \to U(1)$ and the action (5) becomes equivalent to the standard QED.

The fact that not all the χ^2 values are acceptable is uncomfortable and it seems reasonable to look for an alternative that not only incorporate the kinetic mixing but also all possible values of χ.

Then instead of (1), we propose the kinetic mixing

$$F_{\mu\nu}(A)\tilde{F}^{\mu\nu}(X) \equiv F(A)\tilde{F}(X) = \tilde{F}(A)F(X), \tag{7}$$

where the dual tensor is $\tilde{F}^{\mu\nu}(A) = \frac{1}{2}\epsilon^{\mu\nu\rho\lambda}F_{\rho\lambda}(A)$.

The dynamics between both photons is given now by the Lagrangian

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4e^2}F^2(A) - \frac{1}{4}F^2(X) + \frac{\chi}{2e}\tilde{F}(A)F(X). \tag{8}$$

Note first that (7) is gauge invariant but violates CP symmetry and therefore Lagrangian (8) does. This last fact, however, is not a problem because there is no a physical basis for discarding this possibility. The coupling is also a boundary term which is irrelevant except for topologically nontrivial field configurations of X and/or for a space-time with boundaries, and therefore we will keep it until the end of the calculation.

Under this assumptions, the inclusion of matter discussed in (5) is described now by

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - A\!\!\!/ - m)\psi - \frac{1}{4e^2}F^2(A) - \frac{1}{4}F^2(X)) + \frac{\chi}{2e}F(A)\tilde{F}(X). \tag{9}$$

It is possible to diagonalize (9) and in doing so we only have to take care of the electromagnetic part $\mathcal{L}_{\text{gauge}}$ in (8). In fact, let us perform a non-local transformation from the gauge fields $\{A_\mu, X_\nu\}$ to $\{A_\mu, A'_\nu\}$ as follow

$$F_{\mu\nu}(A') = F_{\mu\nu}(X) - \frac{\chi}{2e}\epsilon_{\mu\nu\lambda\rho}F^{\lambda\rho}(A), \tag{10}$$

which satisfies

$$F^2(A') = F^2(X) - \frac{\chi^2}{e^2}\,F^2(A) - \frac{2\chi}{e}\,F(X)\tilde{F}(A). \tag{11}$$

From this expression is direct to check that the Lagrangian (8) is now decoupled and read

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4e^2}(1+\chi^2)F^2(A) - \frac{1}{4}F^2(A'). \tag{12}$$

In terms of local and gauge invariant quantities, namely the electric and magnetic fields, the Lagrangian (8) is

$$\mathcal{L}_{\text{gauge}} = \frac{1}{2e^2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{1}{2}\left(\mathbf{E}_X^2 - \mathbf{B}_X^2\right) - \frac{\chi}{2e}\left(\mathbf{E}\cdot\mathbf{B}_X + \mathbf{B}\cdot\mathbf{E}_X\right). \tag{13}$$

where a subindex X in the fields denote electromagnetic fields of the dark sector. That is $E_i = F_{0i}(A)$, $(E_X)_i = F_{0i}(X)$ and so on.

Then, from (10) we obtain the fields $\mathbf{E}', \mathbf{B}'$

$$\begin{aligned} \mathbf{E}' &= \mathbf{E}_X - \frac{\chi}{e}\,\mathbf{B}, \\ \mathbf{B}' &= \mathbf{B}_X + \frac{\chi}{e}\,\mathbf{E}, \end{aligned} \tag{14}$$

and it is direct to show that the Lagrangian in (13) becomes

$$\begin{aligned} \mathcal{L}_{\text{gauge}} &= \frac{1}{2e^2}(1+\chi^2)\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{1}{2}\left(\mathbf{E}'^2 - \mathbf{B}'^2\right) \\ &= -\frac{1}{4(e_{(+)})^2}F^2(A) - \frac{1}{4}F^2(A'), \end{aligned} \tag{15}$$

where the electric charge now is redefined as

$$e_{(+)} = \frac{e}{\sqrt{1+\chi^2}}. \tag{16}$$

Note that this rescaled charge is valid for any value of χ and, therefore although it violates CP, the quantum theory is unitary. By the other hand, Lagrangian (12) is not CP invariant neither. This last statement can be verified directly through, for example, the relations in (14), which are modified under CP transformation as follow

$$\begin{aligned} \mathbf{E'}_{\rm CP} &= -\mathbf{E'} - 2\frac{\chi}{e}\mathbf{B}, \\ \mathbf{B'}_{\rm CP} &= \ \mathbf{B'} - 2\frac{\chi}{e}\mathbf{B}. \end{aligned} \tag{17}$$

Both kinetic mixing procedures – namely, couplings (1) and (7) – are described independently by one of the following Lagrangians which includes fermionic matter

$$\mathcal{L}_{(\pm)} = \bar{\psi}(i\partial\!\!\!/ - e_{(\pm)}A\!\!\!/ - m)\psi - \frac{1}{4}F_{\mu\nu}(A)F^{\mu\nu}(A) - \frac{1}{4}F_{\mu\nu}(X')F^{\mu\nu}(X')), \tag{18}$$

with

$$e_{(\pm)} = \frac{e}{\sqrt{1 \pm (\chi_{\pm})^2}}, \tag{19}$$

where we have chosen different couplings for the two different terms, namely $\chi_{(+)}$ for (1) and $\chi_{(-)}$ for (7).

Even though this charge redefinition seems unobservable, one note that it happens in the context of interaction of the dark sector with observable fields and it might also happen –because we do not know exactly the dark matter dynamics– that the dark photon acquires mass ($m_{\gamma'}$), *e.g.* by spontaneous symmetry breaking, and in such conditions a photon oscillation process could take place [10, 11].

The conversion probability for photon oscillation is therefore rescaled through the charge rescaling. This rescaling have an effect in the mass of the hidden photon because $m_\gamma \propto e^2_{(\pm)}$ (depending on the coupling under discussion) and also in the probability itself which is proportional to $e^2_{(\pm)}$. In fact, consider a beam of dark photons γ' with energy $E_{\gamma'}$ and momentum $\mathbf{p}$ which oscillate to visible photons γ with momentum $\mathbf{p}$ and energy E while traveling a time T. Then, the probability of conversion to visible photons, for the two couplings here considered, is [10]

$$P^{(\pm)}_{\gamma'\to\gamma} \propto \frac{1}{1 \pm (\chi_{(\pm)})^2}\sin^2\left(\frac{|\Delta E|\,T}{2}\right), \tag{20}$$

where $|\Delta E| = |E - E_{\gamma'}| = ||\mathbf{p}| - \sqrt{\mathbf{p}^2 + m^2_{\gamma'}}| \approx \frac{m^2_{\gamma'}}{|\mathbf{p}|} = \frac{m^2_{\gamma'}}{E}$.

The last formula implies that the ratio between both probabilities turn out to be

$$\frac{P^{(-)}_{\gamma'\to\gamma}}{P^{(+)}_{\gamma'\to\gamma}} = \frac{\sin^2\left(\frac{\kappa}{1-(\chi_{(-)})^2}\right)}{1-(\chi_{(-)})^2}\,\frac{1+(\chi_{(+)})^2}{\sin^2\left(\frac{\kappa}{1+(\chi_{(+)})^2}\right)}, \tag{21}$$

with κ a constant.

Thus, we conclude that only for $|\chi_{(+)}| = |\chi_{(-)}|$ the conversion probabilities satisfy $P^{(-)}_{\gamma'\to\gamma} > P^{(+)}_{\gamma'\to\gamma}$ and then the CP-violating scenario is less favorable in the sense that this contribution might be less important to the excess of photons observed. However, for the general case $\chi_{(+)} \neq \chi_{(-)}$, it is possible to have $P^{(-)}_{\gamma'\to\gamma} << P^{(+)}_{\gamma'\to\gamma}$ and then, the CP-violating conversion is the most relevant.

Thus, even in absence of precise observational data, we can conclude that excess of gamma radiation could be attributed to a combination of (1) and CP violation processes (7).

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[1] Some reviews are; G. Bertone, D. Hooper and J. Silk, Phys. Rept. 405, 279 (2005); G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996) [hepph/ 9506380].

[2] J. L. Hewett, H. Weerts, R. Brock, J. N. Butler, B. C. K. Casey, J. Collar, A. de Gouvea and R. Essig *et al.*, arXiv:1205.2671 [hep-ex].
[3] W. N. Johnson, III, F. R. Harnden, Jr. and R. C. Haymes, Astrophys. J. 172, L1 (1972); M. Leventhal, Astrophys. J. 183, L147 (1973); G. H. Share, R. L. Kinzer, J. D. Kurfess, D. C. Messina, W. R. Purcell, E. L. Chupp, D. J. Forrest and C. Reppin, Astrophys. J. 326, 717 (1988); R. L. Kinzer et al., Astrophys. J. 559, 282 (2001); D. Attie et al., Astron. Astrophys. 411, L71 (2003); G. Vedrenne et al., Astron. Astrophys. 411, L63 (2003); J. Knödlseder et al., Astron. Astrophys. 411, L457 (2003).; G. Weidenspointner et al., Astron. Astrophys. 450, 1013 (2006); B. J. Teegarden et al., Astrophys. J 621, 296 (2005).
[4] T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, N. L. Rodd and T. R. Slatyer, arXiv:1402.6703 [astro-ph.HE].
[5] P. A. R. Ade *et al.* [Planck Collaboration], arXiv:1502.01589 [astro-ph.CO].
[6] For recent results see *e.g.*, F. Calore, I. Cholis and C. Weniger, JCAP **1503** (2015) 038 [arXiv:1409.0042 [astro-ph.CO]]; M. Abdullah, A. DiFranzo, A. Rajaraman, T. M. P. Tait, P. Tanedo and A. M. Wijangco, Phys. Rev. D **90**, no. 3, 035004 (2014); S. Ipek, D. McKeen and A. E. Nelson, Phys. Rev. D **90**, no. 5, 055021 (2014) [arXiv:1404.3716 [hep-ph]].
[7] B. Holdom, Phys. Lett. B **166**, 196 (1986).
[8] M. Pospelov, Phys. Rev. D **80**, 095002 (2009) [arXiv:0811.1030 [hep-ph]]; M. Pospelov and A. Ritz, Phys. Lett. B **671**, 391 (2009) [arXiv:0810.1502 [hep-ph]]; M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B **662**, 53 (2008) [arXiv:0711.4866 [hep-ph]].
[9] M. Ahlers, H. Gies, J. Jaeckel, J. Redondo and A. Ringwald, Phys. Rev. D **77**, 095001 (2008) [arXiv:0711.4991 [hep-ph]]; M. Ahlers, H. Gies, J. Jaeckel, J. Redondo and A. Ringwald, Phys. Rev. D **76**, 115005 (2007) [arXiv:0706.2836 [hep-ph]]; R. Essig, J. A. Jaros, W. Wester, P. H. Adrian, S. Andreas, T. Averett, O. Baker and B. Batell *et al.*, arXiv:1311.0029 [hep-ph].
[10] L. B. Okun, Sov. Phys. JETP **56**, 502 (1982) [Zh. Eksp. Teor. Fiz. **83**, 892 (1982)].
[11] H. Georgi, P. H. Ginsparg and S. L. Glashow, Nature **306**, 765 (1983).